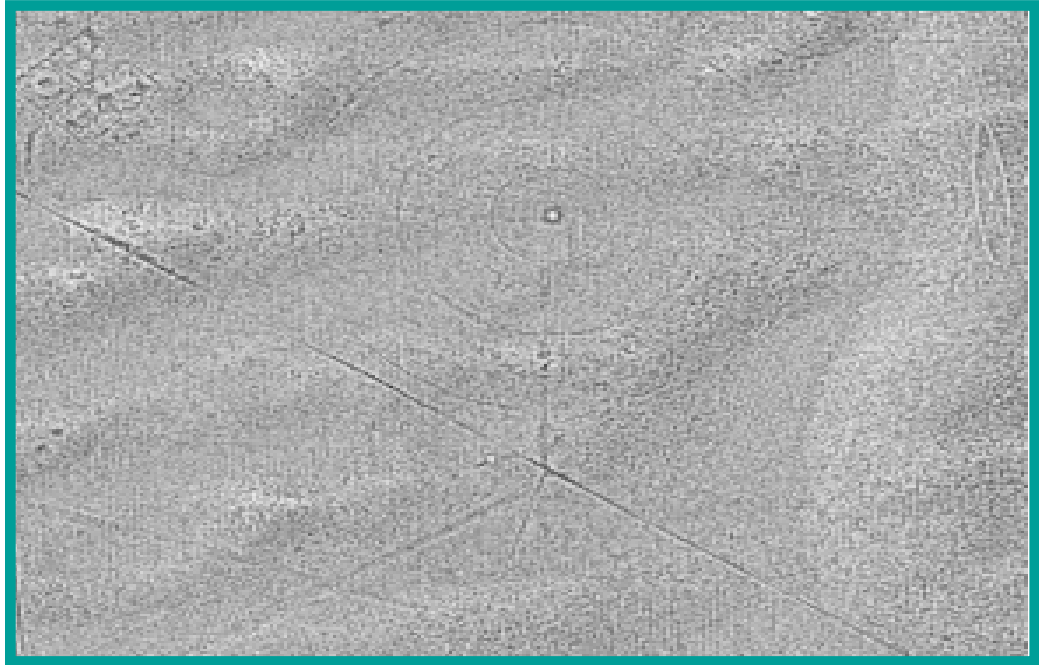


ESTCP

Cost and Performance Report

(MM-0534)



High Density LiDAR and Orthophotography in UXO Wide Area Assessment

January 2008



ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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ACRONYMS AND ABBREVIATIONS

AOI	area of interest
ASR	Archive Search Report
CAD	computer-aided design
CSM	conceptual site model
DBT	Demolition Bombing Target
DoD	Department of Defense
EM	electromagnetic
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
GIS	Geographical Information System
GPS	Global Positioning System
HE	high explosive
IMU	inertial measurement unit
LiDAR	light detection and ranging
MEC	munitions and explosives of concern
MM	Munitions Management
MRS	munitions response site
NDIA	New Demolition Impact Area
PAWS	Phased Array Warning System
PBR	Precision Bombing Range
QA	quality assurance
QC	quality control
SAR	synthetic aperture radar
SORT	simulated oil refinery target
TRSI	Terra Remote Sensing, Inc.
UXO	unexploded ordnance
WAA	Wide Area Assessment

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

Since 2005, Environmental Security Technology Certification Program's (ESTCP) Wide Area Assessment (WAA) Pilot Program has explored the use of an integrated suite of airborne and ground-based technologies as a means to streamline the WAA process. Light detection and ranging (LiDAR) and orthophotography, the subjects of this demonstration, were used in conjunction with synthetic aperture radar (SAR), hyperspectral sensing, helicopter-based magnetometry, and towed-array magnetometry and electromagnetic induction (EMI), along with approaches to statistical modeling of transect design, in an integrated Geographical Information System (GIS)-based analytical environment.

The first phase of the WAA Pilot Program examined three sites—the Pueblo Precision Bombing Range (PBR) site near Pueblo, Colorado; the Kirtland PBR site near Albuquerque, New Mexico; and the Victorville DBT “Y” site near Victorville, California. All three sites were desert bombing ranges with little vegetation and few nonmilitary land uses. The results of the first phase were positive. The combination of technologies employed were successfully used to locate munitions response sites (MRS) and munitions-related features to correct the initial conceptual site model (CSM) and to support further investigation by more expensive technologies that directly detect munitions components. The combination of technologies employed in the Pilot Program was cost-effective and provided a high degree of cross-validation, resulting in higher confidence in the overall results.

As a result, a second phase was added to the program, including two additional sites. The first site, Former Camp Beale, is located approximately 20 miles from Marysville, California, just to the east of Beale Air Force Base. The site covers approximately 18,263 acres (2,391 hectares) and is more complex than the Phase 1 sites, with more vegetation types, more complex topography, and a wider variety of land uses. The second site was the Toussaint River site near Lake Erie, which was primarily an underwater detection site.

URS Corporation provided and analyzed LiDAR and orthophotography data for the Kirtland, Victorville, and Former Camp Beale sites. This Cost and Performance Report summarizes the results of this work. Results are described in more detail in the Final Report for the Kirtland and Victorville sites and the Final Report Addendum for the Former Camp Beale site.

The objective of the demonstration was to document and validate the ability of LiDAR and orthophotography to contribute to the WAA process by:

- Identifying MRS and individual munitions-related ground features
- Providing information about the site and the MRS to support future investigation, prioritization, and cost estimation
- Providing information to support regulatory decisions, including decisions as to requirements for further investigation, institutional controls, or no further action
- Describing the certainty associated with the initial CSM and examining the incremental contributions of each technology to improvements in that certainty.

An additional objective was to develop information about the factors that would affect the cost and performance of both technologies, including the relationship between levels of effort and confidence in conclusions. Performance factors tested included orthophoto and LiDAR data density, flight line orientation, and at the Former Camp Beale, preliminary investigation of vegetation effects. Data artifacts and noise effects were observed and documented.

These objectives were met. LiDAR and orthophoto data were successfully used to identify MRS and munitions-related features and to verify and correct the initial CSM at all three sites. ESTCP successfully used the LiDAR and orthophoto data to plan subsequent phases of the demonstration, including the use of helicopter and ground-based magnetometry and EMI sensing and site reconnaissance. The demonstration, including the validation activities conducted following data acquisitions, provided important insights regarding the appropriate uses, data processing methods, cost and performance factors, and confidence levels for both technologies. All positional accuracy specifications were met. The demonstration provided information as to the advantages and limitations of these technologies.

Advantages include the following:

- Rate of coverage of 5,000 acres or greater per day
- Ability to delineate MRS and munitions and explosives of concern (MEC)-related features
- Contribution to planning and risk assessment
- Increased confidence through cross-validation with other technologies
- Detailed topographic data that can be used in subsequent phases of site investigation, site remediation, and range management.

Limitations include the following:

- Inability to directly detect munitions or their components.
- Detection depends on the persistent or continued presence of surface features. Features can be subject to erosion or destruction from human or animal activities.
- Orthophotos do not contain elevation information.
- Orthophotos do not “look through” vegetation, and LiDAR point densities will be lower in vegetated areas.

The results from the three demonstration sites support the premise of the WAA Pilot Program that LiDAR and orthophotos should be the first technologies to be deployed after completion of the Archive Search Report (ASR) and the initial CSM, and that LiDAR and orthophoto acquisition should be followed with technologies that directly detect munitions components.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

2.1.1 Technology Background

LiDAR is a well-established airborne technology for modeling ground surfaces. Topographic LiDAR was first developed in the late 1960s and early 1970s and has been used for terrain profiling since the mid-1980s. LiDAR has been in wide commercial use since around 1993, and the accuracies and limitations of LiDAR for surface modeling are well documented.

LiDAR uses the time of return for a laser pulse to be reflected back to the sensor to measure the elevation of the point of reflection. Use of Global Positioning System (GPS) and inertial measurement unit (IMU) technology to locate the sensor precisely in the air allows for the accurate calculation of the point of reflection of the laser signal from the ground, buildings, or vegetation. Multiple returns from a single laser pulse can be detected, increasing the chance of sampling the ground surface through gaps in vegetation. Once elevation data is collected in the form of LiDAR points, surface models are created and analyzed. The surface modeling process is typically conducted using standard GIS software and methods, and much of the process can be successfully automated. LiDAR vendors typically guarantee a vertical accuracy of 0.15 m and a horizontal accuracy of 0.3–0.75 m.

The development of higher speed (50–100-kHz) laser scanners, beginning around 2002, has significantly improved the ability of LiDAR to locate small features. Currently, high-speed LiDAR systems are being used to characterize objects in the sub-meter range, such as power line insulators (see Figure 1). The accuracy and data density of current LiDAR systems suggest that the technology could be used to detect ground features indicative of munitions use, including targets and craters, and that the presence of these features could in turn be used to develop more accurate locations of MEC.

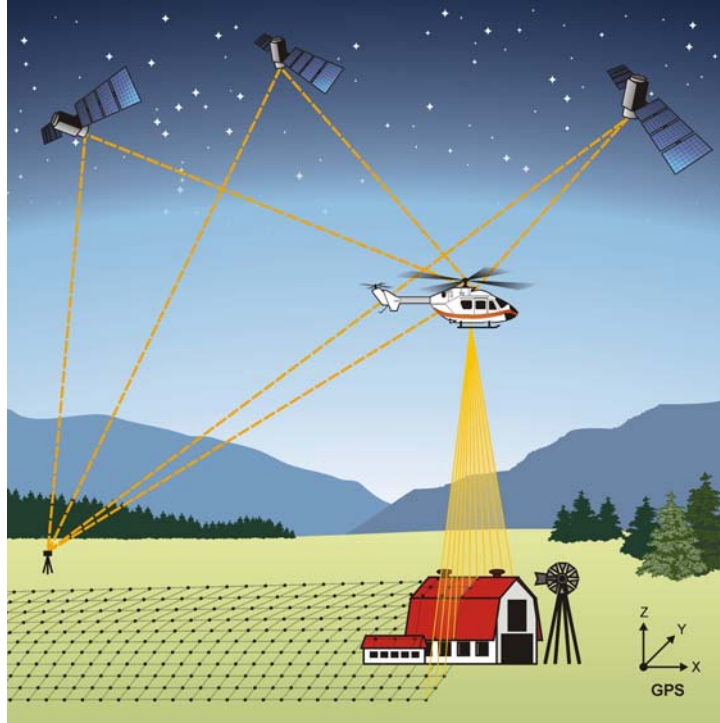


Figure 1. LiDAR System Operations.

Digital orthophotography has been commercially available since the early 1980s, with steady improvement in the resolution (i.e., pixel size) and precision (i.e., pixel placement) of the images as the technology of digital cameras, GPS, and IMU systems has advanced. Since the mid-1990s, image size has advanced from 1,500 pixels across an image to 4,500 pixels. This has allowed for increased flying heights and a reduced number of images for a given area, with consequent cost savings. Commensurate with this improvement has been a twofold increase in the accuracy of the IMU, allowing for accurate positioning of image pixels at a higher flying height (see Figure 2).



Figure 2. Helicopter-Mounted LiDAR and Orthophoto Sensor Equipment.

Airborne digital cameras have been successfully integrated with LiDAR sensors. Cameras with an image density of roughly 4,000 x 4,000 pixels are generally favored because the width of the images collected is very similar to that of the typical LiDAR point swath. Once collected, individual digital images are mosaiced and color-balanced, and the resulting composite image is orthorectified using the LiDAR data. Orthorectification allows for the accurate location of each photo pixel, eliminating distortion caused by camera angle and topography. Vendors generally guarantee a horizontal accuracy of 3 pixel widths compared to ground control for orthophotography.

Digital images are collected concurrently with LiDAR and, because the two sensors use the same GPS and IMU, the two data sets can be integrated very accurately. Vendors generally guarantee spatial integration of orthophotos and LiDAR within 2 pixel widths. Final orthophoto pixel size depends on the flight altitude and the camera specifications; helicopter-based cameras flying at altitudes of 400–450 m are capable of pixel sizes of approximately 10 cm. Smaller pixel sizes than this are generally impractical due to the low flight elevations and slow flight speeds required to collect properly overlapping images, and the very large numbers of images that would need to be mosaiced.

The ability to produce spatially accurate orthophotos with relatively small pixel sizes suggests that this technology could be used to identify munitions-related features, and to cross-validate technologies such as LiDAR.

2.2 PROCESS DESCRIPTION

2.2.1 Mobilization, Installation, and Operational Requirements

At all three sites, flight line planning for the LiDAR/orthophoto and LiDAR only flights was conducted by Terra Remote Sensing, Inc. (TRSI), the ortho/LiDAR vendor used for this demonstration, in the weeks prior to mobilization. Flight lines were planned to ensure complete site coverage, minimize the number of turns, and achieve planned overlap. At the Kirtland site, flight lines were planned to minimize interactions between data collection and air traffic at the Double Eagle Airport. Digital imagery was planned for acquisition at periods of low sun angle. Previous testing had shown that the shadows created by low sun angle were useful in detecting shallow features.

The LiDAR and orthophoto sensor system was installed into a Bell 206B helicopter owned by a local helicopter vendor (see Figure 3). Renting helicopters (and pilots) using local vendors is a standard industry practice that allows the LiDAR vendor to ship only the sensor package rather than the aircraft. The use of local helicopter vendors also allows for the use of local pilots who have better knowledge of local weather patterns and flight clearance requirements.



Equipment installation



Sensor pod mounted below helicopter, control console visible through window

Figure 3. LiDAR and Orthophoto System Installed on Helicopter.

Data collection flights were begun once mobilization, sensor installation, and calibration flights had been completed. The period for data collection included an additional day to permit re-acquisition of any missed or erroneous areas discovered during daily quality assurance/quality control (QA/QC) review.

2.2.2 Data Processing Steps

Processing of the sensor output to create LiDAR points was performed by TRSI. Following return of the data to the office, calibration factors determined in the field were checked, fine-tuned, and applied to laser range, GPS, and IMU data to produce xyz values for each point. LiDAR points were then transformed into the delivery datum and projection, and coded to indicate returns from ground versus nonground surfaces. Additional fields for each point included the intensity value, GPS date, and flight line number. LiDAR points were exported as text files for delivery to URS. LiDAR data from each LiDAR flight was processed and delivered separately to allow for separate analysis of data from each flight altitude.

Digital image processing was done by TRSI. The procedure included mosaicing of the individual digital images collected during flight, transformation of the consolidated image to the delivery datum and projection, orthorectification using the LiDAR data, color balancing, and trimming to the delivery tiles.

2.2.3 Selection of Analytical/Testing Methods

Analysis of LiDAR data is performed by conversion of the processed LiDAR points to usable GIS products such as surface models, contour lines, and hillshades. Creation of these products and their analysis were accomplished by URS using ESRI's ArcGIS software suite. ArcGIS was the only standard computer-aided design (CAD) or GIS product reviewed that would successfully handle the large number of LiDAR points collected. Additionally, ArcGIS is the GIS package most widely used by U.S. government agencies and private contractors. As such, it

is appropriate to develop analysis methods and resulting products that can be duplicated by typical federal facilities managers using existing software tools.

Orthophoto data was analyzed by visual examination of the image to locate potential MRS and munitions-related features.

2.2.4 Safety Issues

Because LiDAR and orthophotos are airborne technologies, they avoid the typical safety concerns related to ground-based munitions investigation. No special safety issues were encountered during data collection related to munitions presence. At the Kirtland site, flight operations were impacted by air traffic at the Double Eagle Airport, located between the north and south portions of the study area. In response, TRSI changed its planned flight lines to avoid the airport runway, and used an additional spotter in the helicopter during data collection flights.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

URS and TRSI conducted a successful demonstration of LiDAR and high-resolution digital imagery at an operational U.S. Navy range near Boardman, Oregon, during November 2004. Both the LiDAR data and the orthophotos were successful in detecting patterns of surface disturbance indicative of unexploded ordnance (UXO)/MEC activities.

Even though the LiDAR data was collected at relatively low density, LiDAR revealed depressions such as craters well. LiDAR was very successful at locating target features such as bull's-eye rings. Disposal craters could be distinguished from bombing practice craters by their patterns on the ground. Orthophotos cross-validated most, though not all, features visible in the LiDAR surfaces. However, surface models created from LiDAR data could be analyzed in ways that orthophoto data could not be, such as measuring the depth of craters.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.4.1 Advantages

- **Rate of coverage.** In an operational setting, data collection rates of 5,000 acres or greater per day can be expected for LiDAR and orthophotos. This compares favorably to maximum collection rates of around 500 acres per day for helicopter-based magnetometry, and 20 acres per day for towed-array magnetometry.
- **Ability to delineate MRS and MEC-related features.** LiDAR and orthophotography successfully revealed MRS and MEC-related surface features at both demonstration sites, even many years after their last use. In the case of the Kirtland and Camp Beale sites, these features were usually not visible to observers on the ground.
- **Enhanced planning and risk assessment.** Because they can cover entire sites relatively quickly and at lower cost, these technologies can be used to locate and prioritize appropriate areas for use of more costly ground-based technologies.

- **Increased confidence through cross-validation.** LiDAR and orthophotos data can contribute to increased confidence levels as their results are combined with those of subsequent technologies. This is particularly true in the determination of un-contaminated areas of the site.
- **Other benefits.** Both technologies provide highly detailed topographic data that can be integrated into a facility's CAD or GIS system and used in subsequent phases of site investigation, site remediation, and range management.

2.4.2 Limitations

- **Munitions detection.** Neither LiDAR nor orthophotography can directly detect munitions or their components such as scrap. Rather, these technologies rely on detection of ground surface features that may indicate past munitions use. Consequently, LiDAR and orthophotos can focus, and perhaps reduce, the need for further investigation with magnetometers or EMI sensors but cannot eliminate it altogether.
- **Elevation data.** Orthophotos do not contain elevation information. In practice, it is sometimes difficult to distinguish small surface depressions from small mounds or shadows using orthophotos alone.
- **Vegetation effects.** Since both LiDAR and orthophotos are light-based technologies, neither will penetrate vegetation. Orthophotos do not "look through" vegetation, and LiDAR point densities will be lower in vegetated areas. However, LiDAR is frequently successful in penetrating small openings between and within vegetation, and this success has increased with the speed of LiDAR sensors and the development of the ability to measure multiple returns.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary performance objectives for these technologies were to:

- Clarify whether and to what extent LiDAR and orthophotos can delineate MRS boundaries and MEC-related features, and contribute to focusing and prioritizing subsequent low-altitude and ground-based work
- Reveal relationships between the density of LiDAR and orthophoto data, their levels of cost, and their ability to accurately locate MRS boundaries and MEC-related ground features
- Clarify whether and to what extent LiDAR and orthophotos can verify, reveal errors in, or improve the accuracy of the initial CSM
- Contribute data and analysis to the overall combination of technologies used in the WAA Pilot Program, in a manner that is timely to the application of the other technologies demonstrated, in formats useable by other demonstrators, and with sufficient positional accuracy compared to project control points to allow meaningful coordination and comparison.

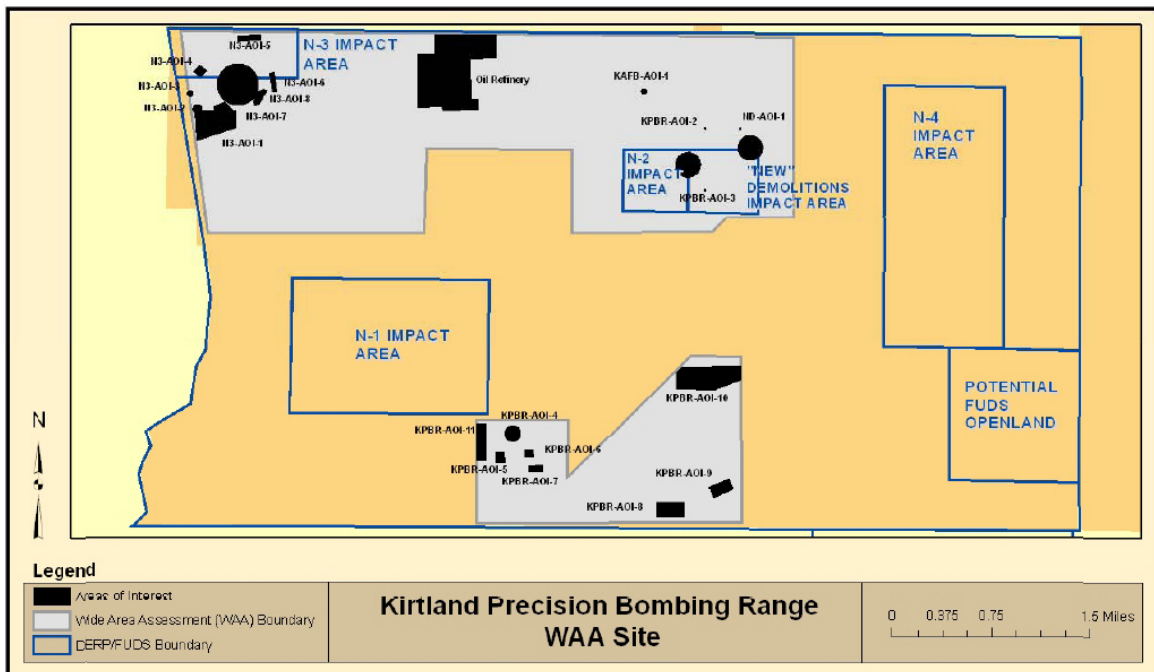
Specific performance criteria and performance metrics related to each of these objectives are documented in the Final Report for each site.

3.2 SELECTION OF TEST SITES

All three demonstration sites were chosen by the ESTCP Program Office. Details of the site selection process can be found in the Final Report for the WAA Pilot Program.

3.3 TEST SITE HISTORY, CHARACTERISTICS, AND PRESENT OPERATIONS

The first demonstration site was located at the Kirtland Air Force Base PBR located approximately 10 miles west of Albuquerque, New Mexico. Figure 4 shows the layout of the Kirtland PBR WAA site. The site is part of a much larger set of bombing ranges used for training purposes during World War II. The study site consisted of approximately 5,120 acres within the PBR, located in two parcels to the north and south of the Double Eagle Airport, the primary small aircraft airport for the Albuquerque area. The study area itself is currently undeveloped, although portions are planned for commercial or industrial development, and airport expansion into the study is possible.



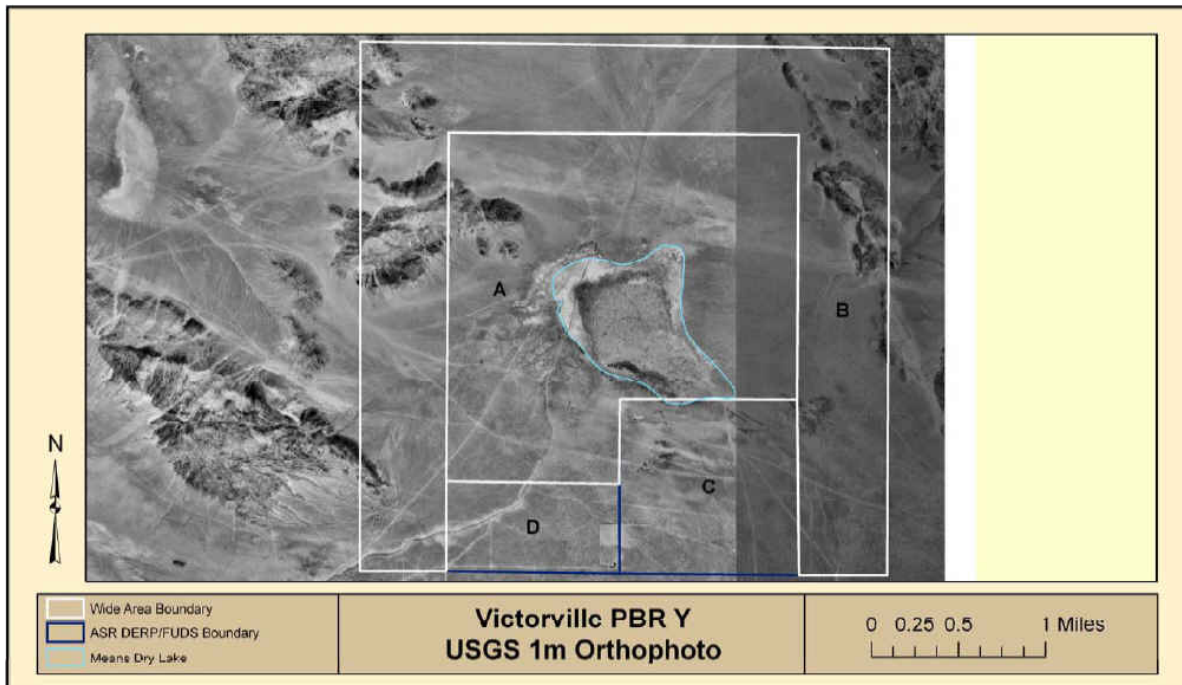
Source: ESTCP (2007a) ESTCP WAA Pilot Program (2008)

Figure 4. Kirtland Precision Bombing Range Site.

The target areas identified in the CSM for the Kirtland site included:

- Target N-2, a 1,000-ft-diameter bull's-eye target used for 100-lb practice bombs
- Target N-3, a 1,000-ft-diameter bull's-eye target used for 100-lb practice bombs and for scrap storage
- The New Demolitions Impact Area (NDIA), a 1,000-ft-diameter high explosive (HE) bull's-eye target
- The Simulated Oil Refinery Target (SORT), a target consisting of 350-ft x 350-ft rectangular cells.

The second demonstration site was located at the Former Victorville Army Air Force Demolition Bombing Target (DBT) Y and PBR 15 (Figure 5). The site is located in San Bernardino County, California, approximately 42 miles southeast of the town of Victorville, California. This site lies within a much larger complex of approximately 23 targets used between 1942 and 1945. The site is managed by the U.S. Bureau of Land Management and is used primarily as a recreation area for off-road vehicles, camping, and target shooting. The demonstration site encompasses approximately 5,640 acres.



Source: ESTCP: Victorville PBR (2007)

Figure 5. Victorville DBT Y and PBR Target 15 Site.

Two target areas were identified in the initial CSM for the Victorville site:

- Target DBT Y, located in Means Dry Lake bed in the center of the demonstration site, identified as a demolition bomb target area where bombs between 100 and 2,000 lbs were used.
- Target PBR 15, a suspected bull's-eye target located in the southeast portion of the demonstration site used for precision bombing practice. According to the initial CSM, PBR 15 was not visited during the ASR site visit and little is known about the area.

The Former Camp Beale site consists of 87,672 acres approximately 10 miles east of Marysville, California, between Yuba and Nevada counties (see Figure 6). The site is located immediately to the east of Beale Air Force Base. The demonstration site was used by the Department of Defense (DoD) for ground ranges, moving target ranges, and bombing ranges between 1943 and 1959. Historic photographs revealed extensive ground disturbances, expected to have been created during previous Munitions Management (MM)-related activities. Other areas from the historical photographs were noted as disturbed, either by ground scarring, visible craters, or other activities. According to the CSM, cleanup activities were conducted in 1947 and 1958–1959. The Former Camp Beale site was excessed and sold between 1959 and 1964 and now contains both private land and state land located within the Spenceville Wildlife Reserve.

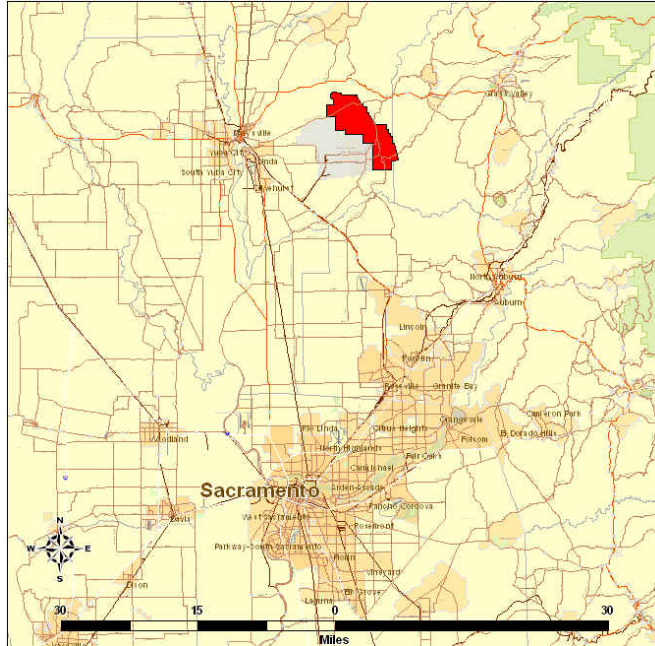


Figure 6. Former Camp Beale Demonstration Site Location.

The CSM identified numerous bombing ranges, firing ranges, and training ranges, often overlapping, but provided little to no information about specific target locations.

3.4 ANALYTICAL PROCEDURES

At all three sites, analysis of the LiDAR and orthophoto data include the following steps:

- Review of the LiDAR surface models and orthophotos to detect missing data, spatial discrepancies, noise effects, or other quality problems. LiDAR and orthophoto spatial accuracy reported by the vendor was independently checked using the site survey control points.
- Visual examination of each LiDAR and orthophoto data set for potential MRS.
- Visual examination of each LiDAR and orthophoto data set for individual features such as craters.
- Suggested modifications to the MRS or target area boundaries from the CSM.
- Examination of the effects of data density and other performance parameters, using the control points, calibration craters, and vertical control structures.

To reduce potential bias, the initial data analysis was conducted by GIS technicians without reference to the CSM. Results of the initial analysis were reviewed by staff with expertise in UXO.

Detailed description of the analytical procedures used is found in the Final Report for the Kirtland and Victorville sites, and the Final Report Addendum for the Former Camp Beale site.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

4.1.1 MRS and Feature Detection, Kirtland Site

At the Kirtland site, data collection flights took place on August 9, 10, and 11, 2005, with a total of 177 flight lines collected. In order to test data density effects, flight lines were collected at three altitudes: 900 m, 450 m, and 300 m. In order to test the effect of flight line orientation, two sets of flight lines were collected at 300 m. For the north portion of the project area, the two flight line sets were flown perpendicular to each other; for the south portion they were flown parallel. Digital images were collected concurrently with LiDAR during the 900 m and 450 m flights, in order to produce orthophotos with 10-cm (4-in) and 20-cm (8-in) pixel sizes.

The Kirtland CSM described four historic bombing sites, one of which did not have a well-defined location. All four were visible in the LiDAR surface models, and one was visible in the orthophotos. Additionally, LiDAR data showed the presence of subtargets not mentioned in the CSM and a potential additional target area. Target objects were detected despite the fact that the berms making up the target were from 15–20 cm in height and generally not visible to crews on the ground. In addition to the main target features, 15 additional sites of interest were detected using the LiDAR data, including seven in the north portion of the site and eight in the south portion. Most consisted of isolated groups of potential craters.

The Kirtland site contained just over 100 small features that were potentially related to munitions use, mostly isolated potential craters. The site also contained numerous linear features, mostly jeep trails and other vehicle tracks. Potential features were visually identified from the LiDAR hillshades and the orthophotos.

A sample of the target objects detected is shown in Figures 7-10.

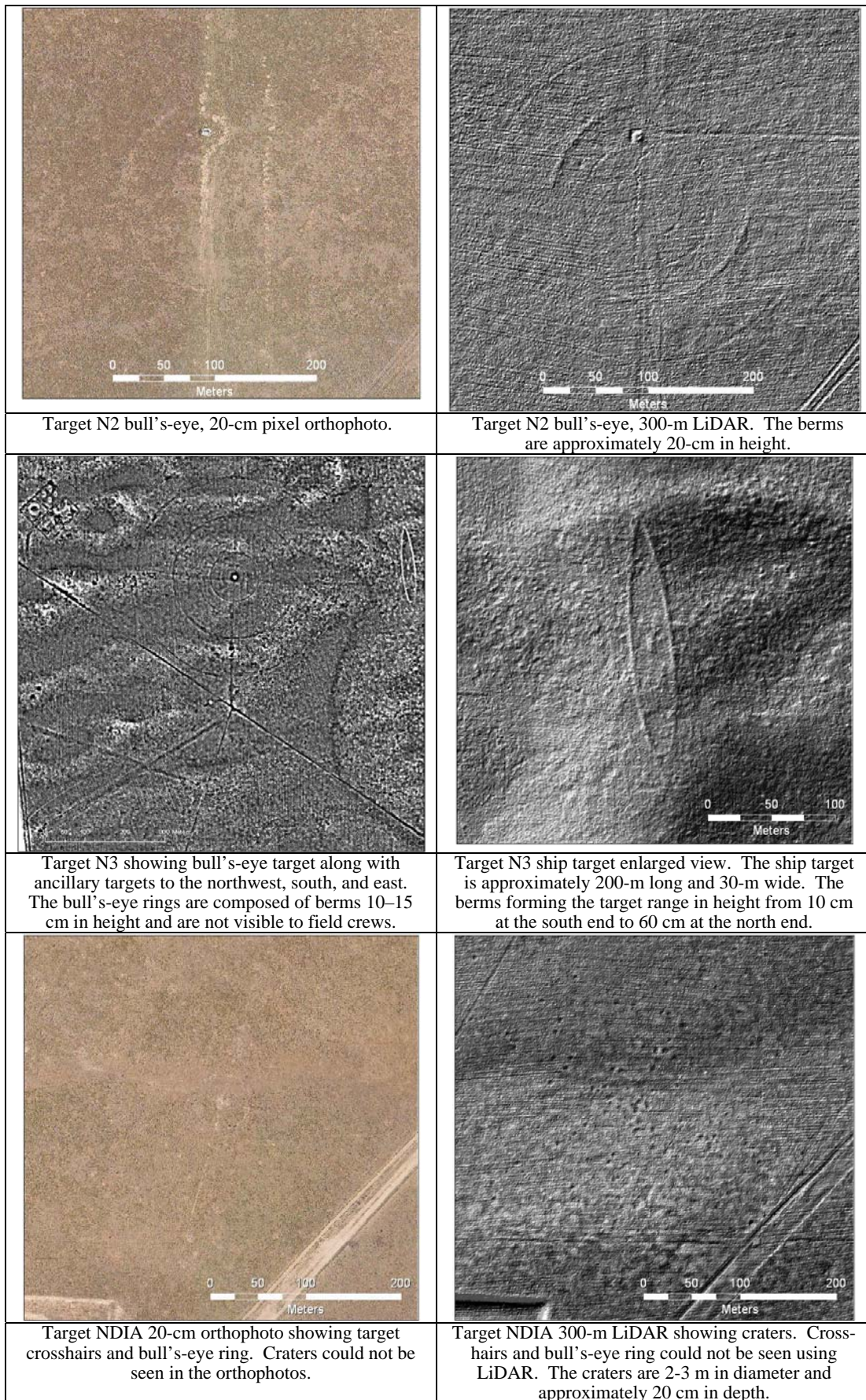


Figure 7. Kirtland Site Bombing Targets.

4.1.2 MRS and Feature Detection, Victorville Site

At the Victorville site, orthophoto data collection flights took place on January 24 and 25, 2006, and LiDAR data collection flights took place on February 3 and 4, 2006. A total of 45 flight lines was collected at two altitudes: 450 m and 300 m. The two flights were flown perpendicular to each other. Digital images were collected concurrently with the 450-m flight in order to produce orthophotos with 10-cm pixels.

The Victorville CSM described two historic bombing sites, a demolition bombing area located in a dry lake bed, and a practice bombing target. Both targets were clearly visible using LiDAR and orthophoto data. No additional sites of interest were detected at Victorville using these technologies. LiDAR data showed numerous craters in and near the DBT. These were used to refine the boundaries of the MRS for the target.

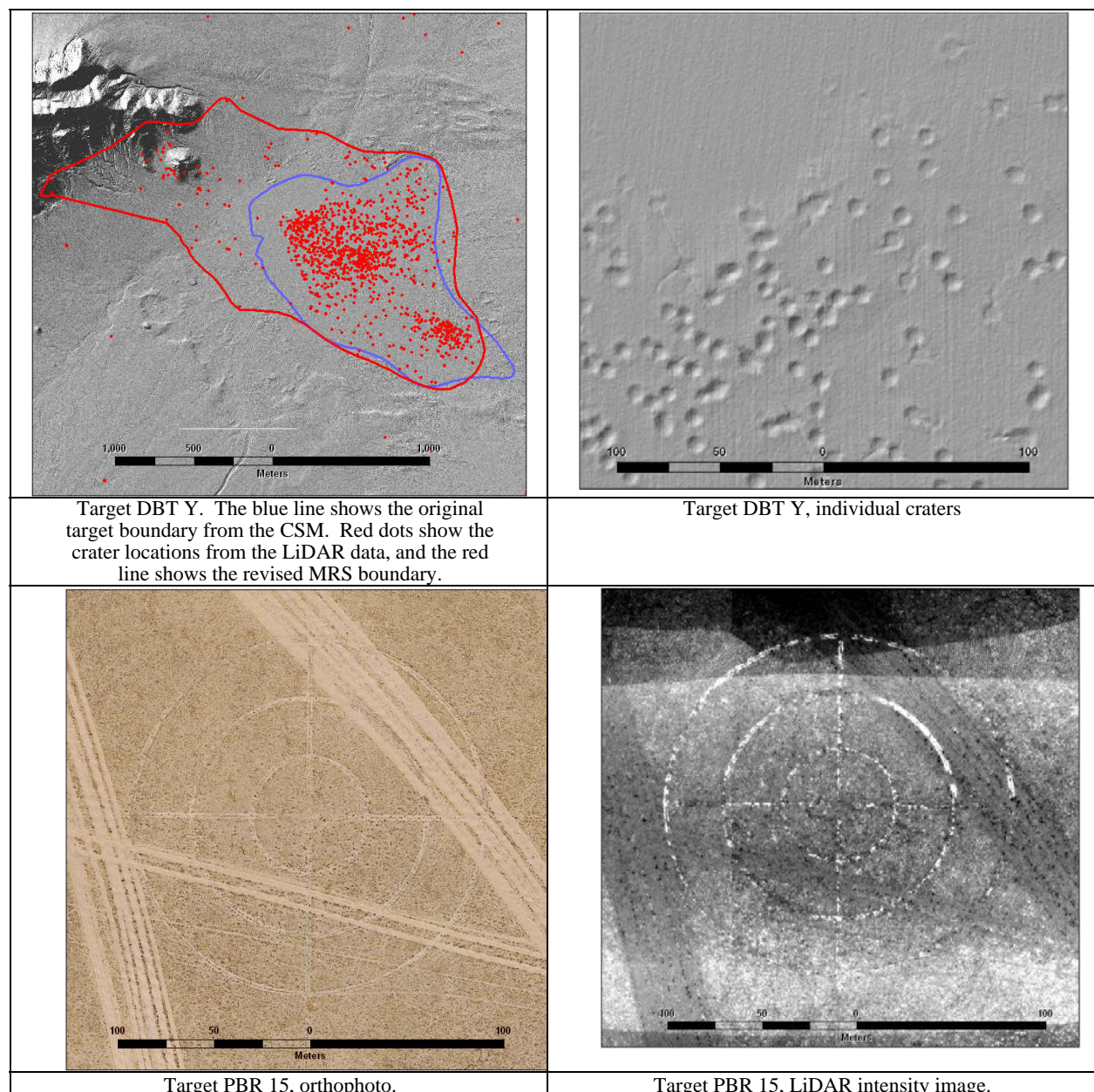
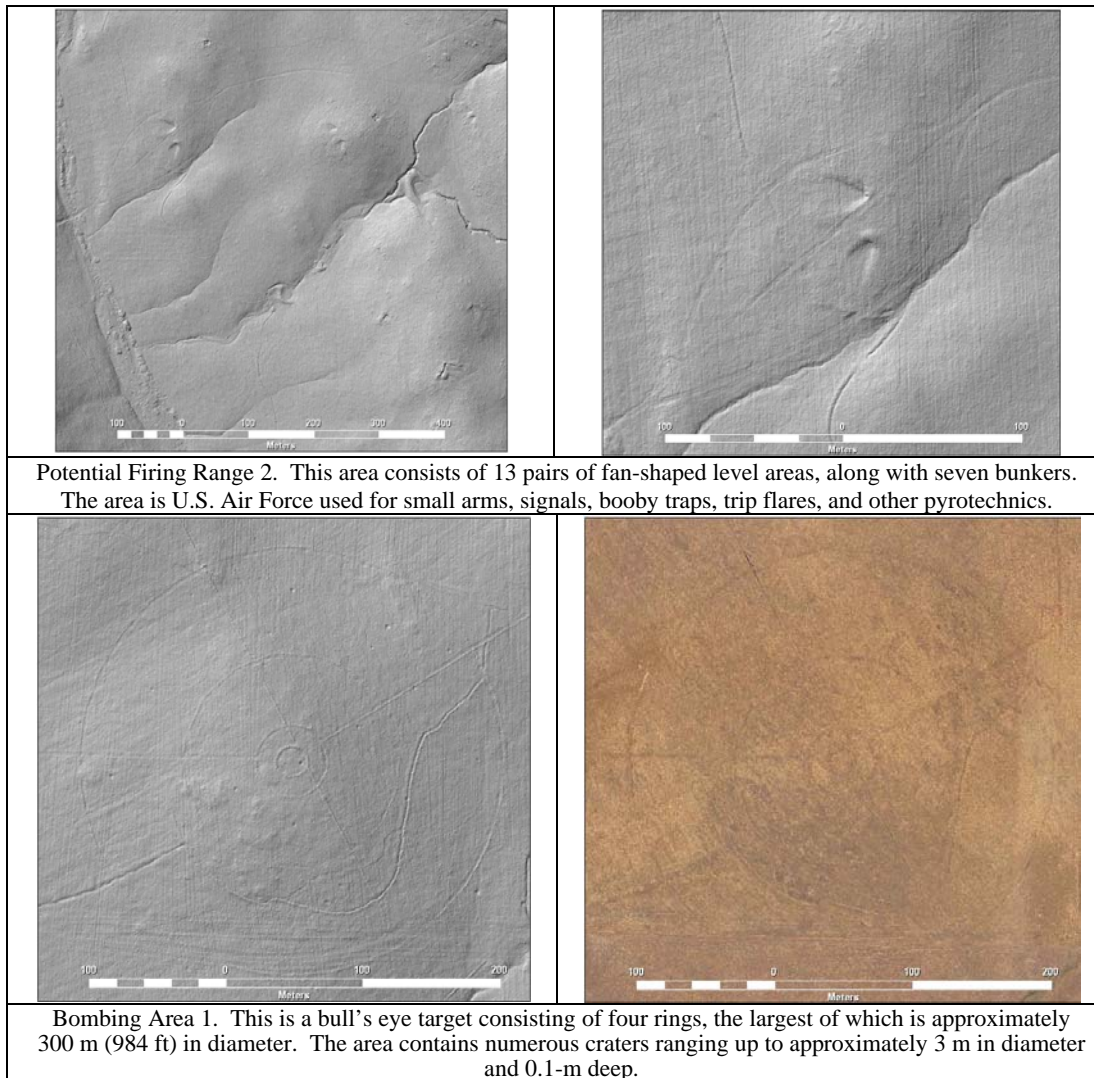


Figure 8. Victorville Site Target Areas.

4.1.3 MRS and Feature Detection, Former Camp Beale Site

At the Former Camp Beale site, data collection flights took place on July 22 through 26, 2006, with a total of 120 flight lines collected at altitudes of 300 and 450 m. Orthophoto data was collected concurrently with LiDAR during the 450-m flight in order to produce images with a 10-cm pixel size.

The Former Camp Beale CSM described a wide variety of bombing areas, training ranges, and firing ranges, often overlapping. No specific target locations were given. Three bombing areas, including one bull's-eye target, were located using the LiDAR and orthophoto data, along with features from two firing ranges. The bull's-eye target was located outside the mapped bombing practice areas in the CSM. Approximately 1,000 individual features were identified (not including craters in two crater fields). Many individual features were ambiguous and their origin could not be determined without further investigation. A sample of the target areas detected is given in the following figures:



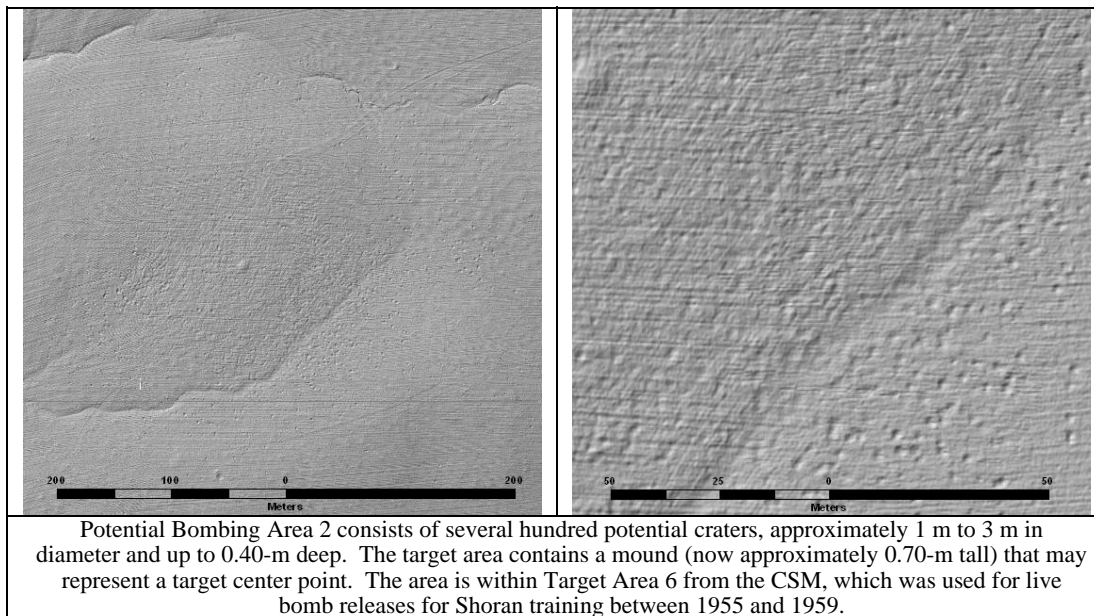
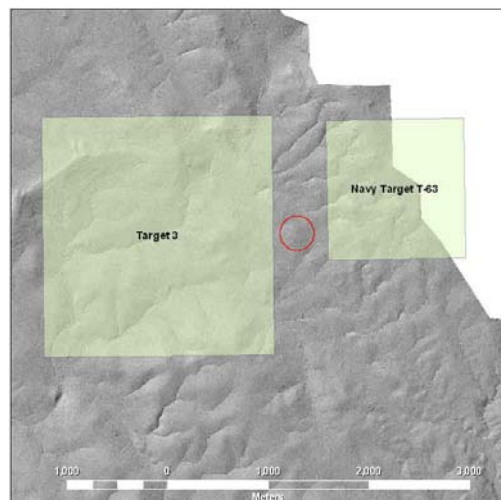


Figure 9. Former Camp Beale Target Areas.

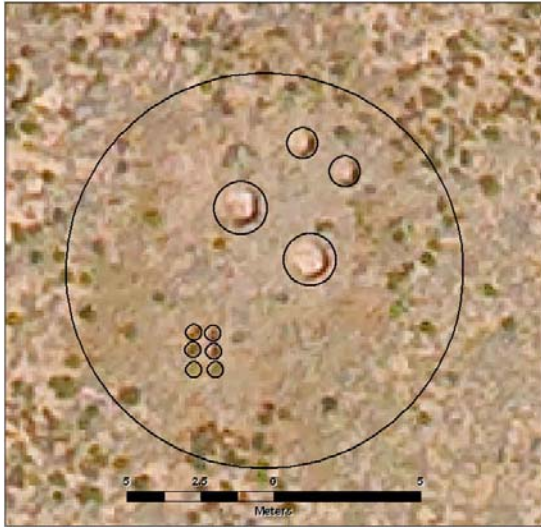


Bombing Area 1 is located between Target 3 and Navy Target T-63 in the CSM, which was used for HE bombing practice from 1948 to 1955. It appears most likely that this is the HE bombing target, and the maps accompanying the initial CSM are somewhat erroneous.

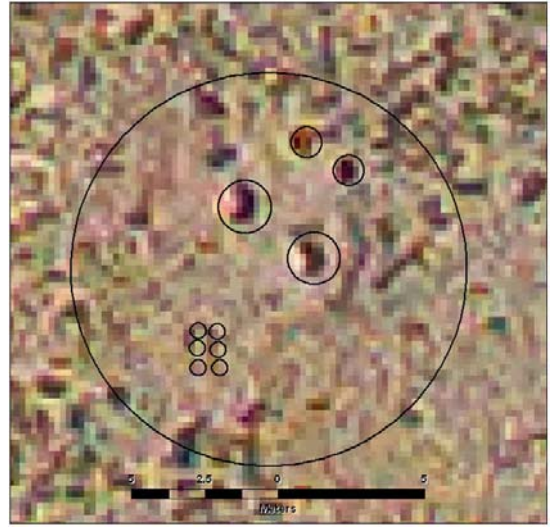
Figure 10. Bombing Area 1 with CSM Areas.

4.1.4 Performance Factors: Data Density Effects

LiDAR and orthophoto data density were found to have a significant effect on the performance of both technologies, up to a point of diminishing returns. For orthophotos, images with a 10-cm pixel size performed significantly better than the 20-cm images collected at the Victorville site, or the 30-cm images that were previously available for the Former Camp Beale site (see Figure 11).



Kirtland site, 10-cm orthophoto with calibration crater locations. Calibration craters are 1.5 m, 1.0 m, and 0.3 m in diameters.



Kirtland site, 20-cm orthophoto with calibration crater locations.



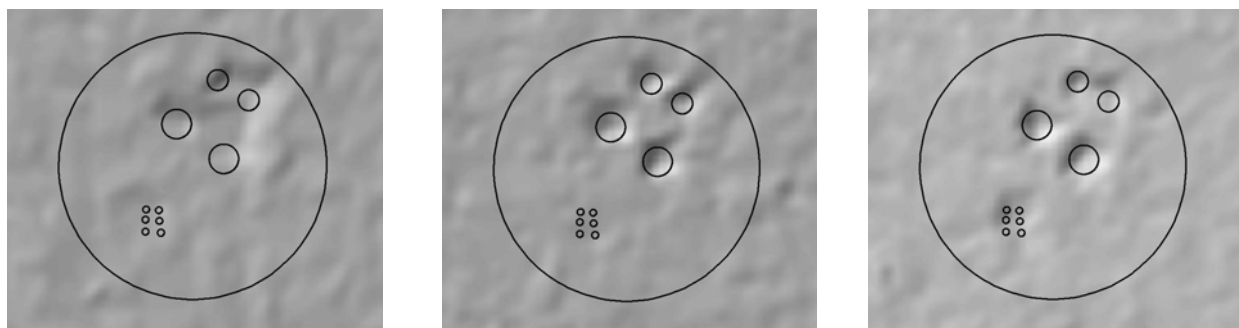
Former Camp Beale site, 10-cm pixel orthophoto with bull's eye aiming target.



Former Camp Beale site, 30-cm (1-ft) pixel orthophoto with bull's eye aiming target.

Figure 11. Orthophoto Data Density Results.

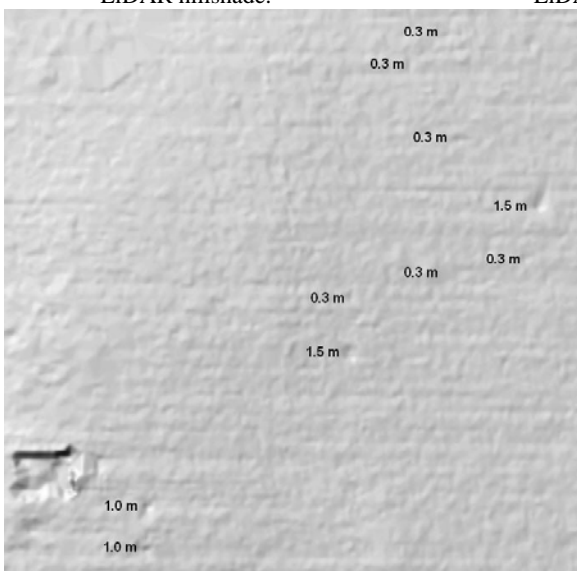
For LiDAR, increasing the LiDAR point density had only a slight impact on detecting large target items but improved the ability to detect smaller items such as the calibration craters, as shown in Figure 12. However, LiDAR was not able to reliably detect the 0.3-m (1-ft) calibration craters at any of the data densities collected. This was true even at the extremely high data density of 13.8 LiDAR points/m² collected at the Former Camp Beale site, a value well above that necessary to delineate craters.



Kirtland site, 900 m (1.6 pts/m²)
LiDAR hillshade.

Kirtland site, 450 m (4.1 pts/m²)
LiDAR hillshade.

Kirtland site, 300 m (6.1 pts/m²)
LiDAR hillshade.



Former Camp Beale site, 13.8 pts/m² LiDAR hillshade with
calibration craters.



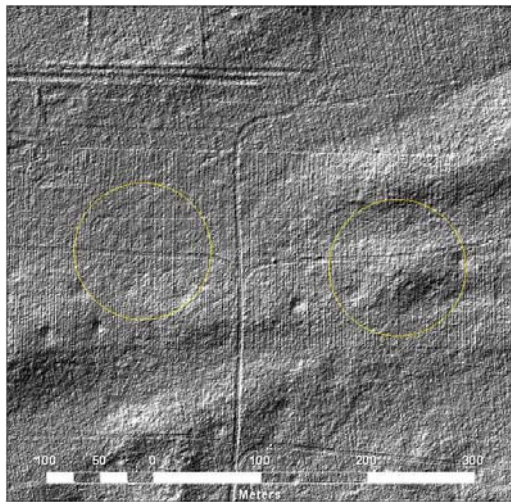
Portion of the image to the left showing LiDAR points, a
1.5-m calibration crater and two 0.3-m calibration craters.
Even at this very high data density, one of the two
calibration craters receives no LiDAR points.

Figure 12. LiDAR Data Density Results.

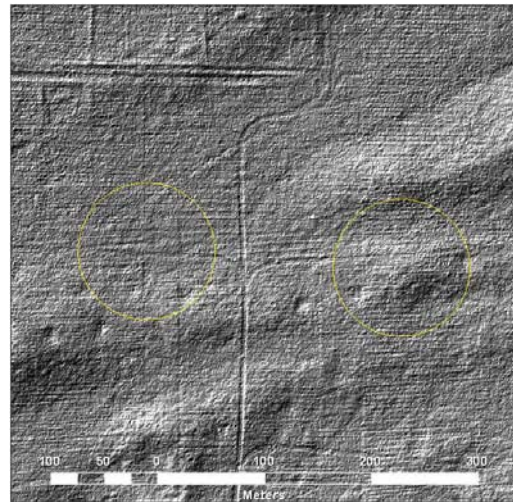
LiDAR data density was found to vary considerably across the test area. This finding may have some implications for detecting small individual features. LiDAR density variations and effects are discussed in detail in the Final Report for the Kirtland and Victorville sites, and the Final Report Addendum for the Former Camp Beale site.

4.1.5 Performance Factors: Flight Line Orientation

Flight line orientation, or the direction the aircraft was flying while the data was being gathered, had an impact on the detection of faint linear features such as dirt roads and shallow berms. Flight line orientation had no discernable impact on crater detection (see Figure 13).



Kirtland site, east-west LiDAR flight lines. East-west roads appear more clearly.



Kirtland site, north-south LiDAR flight lines. East-west roads appear less clearly.

Figure 13. Flight Line Effects.

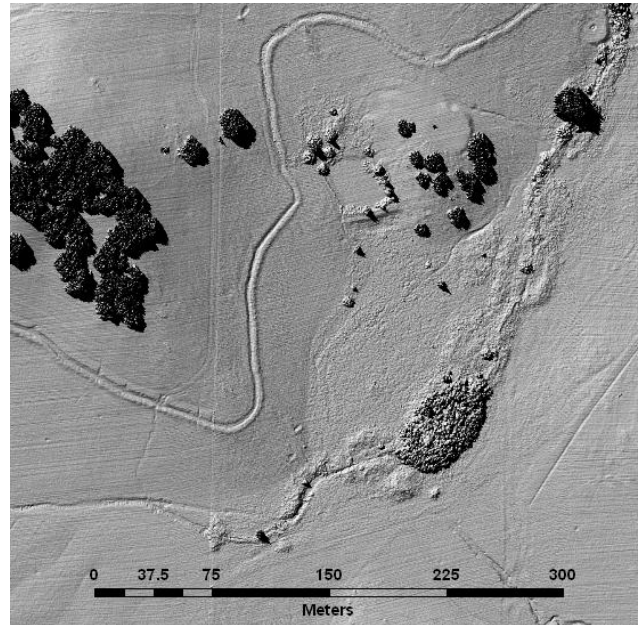
4.1.6 Performance Factors: Vegetation

As a light-based technology, LiDAR does not penetrate vegetation. Nevertheless, LiDAR is often successfully used to model the ground surface under vegetation since LiDAR points will often fall in the many gaps between foliage. In practice, LiDAR has been used to model ground surfaces in all but truly closed canopies.

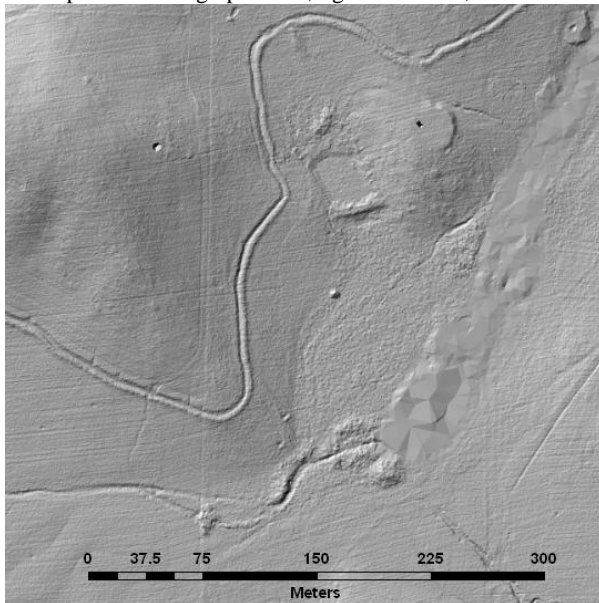
However, while some LiDAR points will penetrate to the ground surface in vegetated areas, most will not. Consequently, the surface model under vegetative cover will be less detailed. As a preliminary attempt to quantify this effect, two areas of $\frac{1}{4}$ km² were modeled. A grid of 2 m cells was created, with each cell assigned the percentage of LiDAR returns that were reflected from a point 3 ft or higher from the ground surface. At these two areas, the forested areas blocked 50% - 80% of the LiDAR points, while in dense brush over 90% of the LiDAR points were blocked. Under the trees, good modeling of the ground surface was nevertheless achieved. This may have been a result of the high overall LiDAR data densities involved. In the area of dense brush, the vegetation effect caused serious degradation of the surface model. The effect is shown in the images in Figure 14.



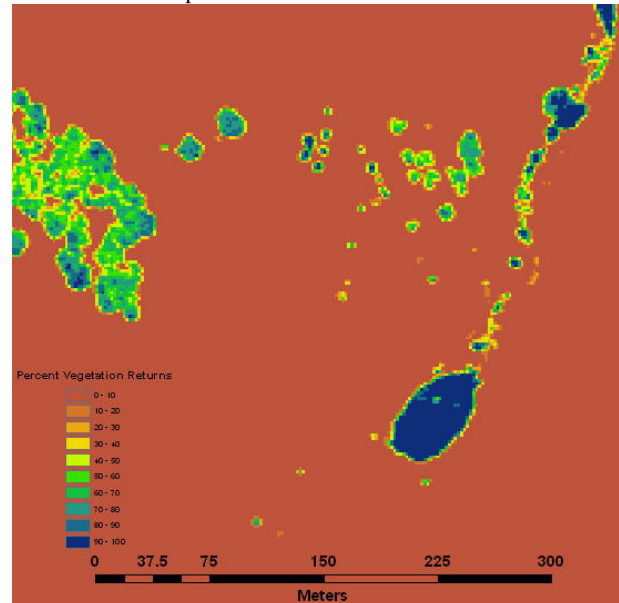
Orthophoto showing open area, light tree cover, and brush.



All points LiDAR surface model.



LiDAR ground surface model. The surface model for the brushy area is severely degraded.

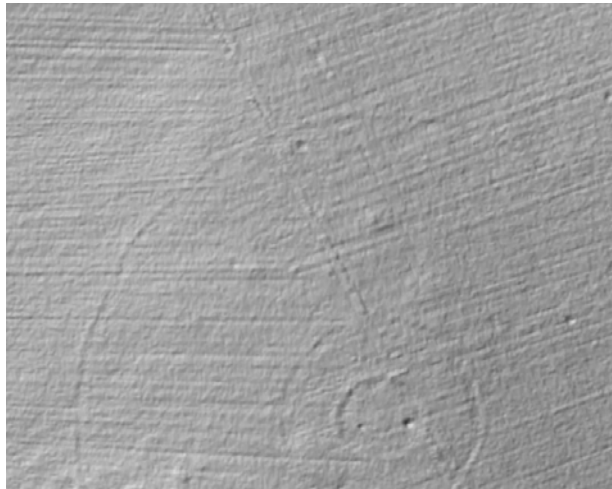


Density map showing the percentage of LiDAR points reflected from vegetation over 3 ft in height.

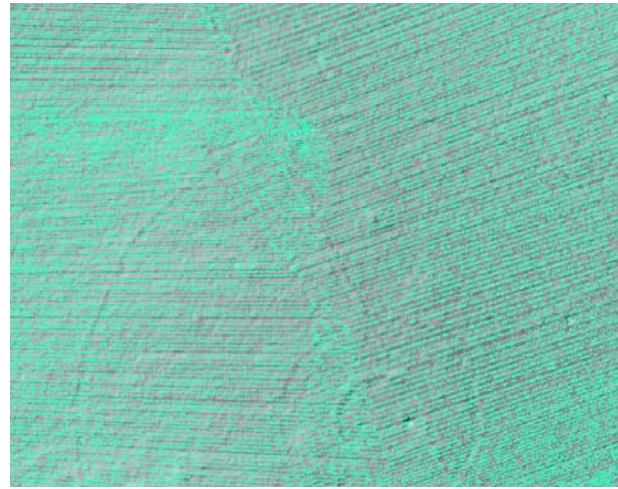
Figure 14. Vegetation Effects on LiDAR Surface Models.

4.1.7 Performance Factors: Data Artifacts and Noise Effects

At all three sites, the LiDAR data showed “corduroy” effects roughly 0.05-m deep in areas of relatively flat, smooth terrain (see Figure 15). This is a common LiDAR artifact, generally believed to result from small errors in the GPS, IMU, and laser range finder that cannot be adjusted out during data processing. The size of the anomaly is well within the vertical accuracy specifications for LiDAR data. The images below show the relationship between the observed “corduroy stripes” in the modeled ground surface and the lines of LiDAR points.



Former Camp Beale site, “corduroy” effect



Former Camp Beale site, “corduroy” effect with LiDAR points

Figure 15. LiDAR Data Artifacts.

4.2 PERFORMANCE CRITERIA

LiDAR and orthophoto data collected for this demonstration met the performance criteria related to data collection, data procession, site coverage and positional accuracy established for each site. Detailed results are given in the Final Report for the Kirtland and Victorville sites and the Final Report Addendum for the Former Camp Beale site.

4.3 DATA ASSESSMENT

The performance data from the three demonstration sites largely supported the performance claims for LiDAR and orthophotos at munitions sites.

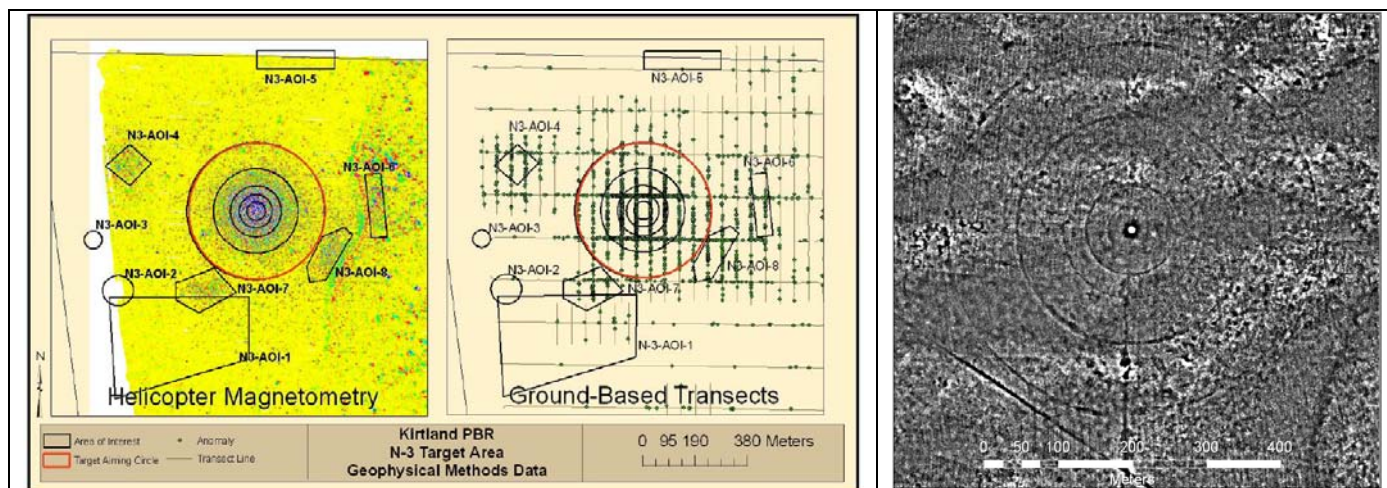
- *Performance.* The LiDAR and orthophoto data met the performance objectives in Table 3-1 of the Demonstration Plan for each site.
 - The two technologies successfully detected and refined the boundaries of MRS at each site. LiDAR was more useful in MRS detection and delineation than orthophotos; however, orthophotos added detection capabilities in some cases that LiDAR did not.
 - LiDAR was successfully used in the detection of individual features, with the success of detection increasing as a function of LiDAR data density to a point of diminishing returns. Detection ability increased substantially between 1.5 pts/m² and 4.5 pts/m², and slightly between 4.5 pts/m² and 6.0 pts/m². Detection ability did not increase past this point. Although the higher densities collected at the Former Camp Beale site (13.8 pts/m²) resulted in very detailed surface models, the added data density did not result in additional feature detection.
- *Personnel/training requirements.* Personnel and training requirements did not differ from standard industry claims. The vendor provided qualified personnel and no issues were noted.

- *Health and safety requirements.* Project health and safety requirements did not differ from standard industry claims. As airborne technologies, LiDAR and orthophotos did not pose the same safety concerns as ground-based technologies. The only health and safety issue encountered was at the Kirtland Air Force Base PBR site, where air traffic from the nearby Double Eagle Airport made it necessary to modify the originally planned flight lines.
- *Ease of operation.* Ease of operation conformed to industry claims for both technologies. Mobilization and demobilization occurred without incident, and data was collected, processed, and delivered in conformance with established specifications and within the established schedule.
- *Limitations.* The limitations of LiDAR and orthophotos did not differ from the general principles presented in Section 2.4, Advantages and Limitations of the Technology. The demonstration further clarified these limitations, as presented in Section 4.1, Performance Data. Specifically:
 - LiDAR and orthophotos identified individual features to approximately 1.0 m in size, but not smaller. This was true even at the very high data density collected at the Former Camp Beale site.
 - Vegetation at the Former Camp Beale site partially obscured the ground surface in some areas. Vegetation cover limited the usefulness of orthophotos in these areas since the images primarily showed vegetation rather than the ground. LiDAR-based surface models were very good quality under the relatively light tree cover and more problematic under brush along stream channels.
 - LiDAR-based surface models showed small noise effects, well within the positional accuracy specifications of the technology.

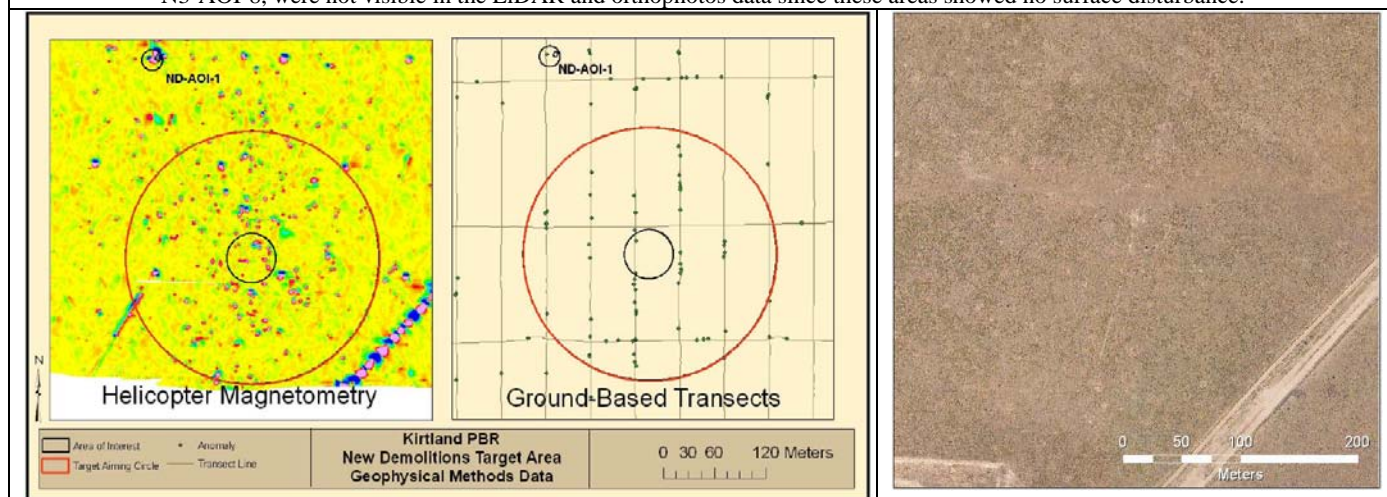
4.4 TECHNOLOGY COMPARISON

The WAA Pilot Program provided an opportunity to compare the performance characteristics of several innovative and existing approaches to site assessment, including helicopter magnetometry, towed-array magnetometry, and electromagnetic (EM) sensing, intrusive investigation, and field reconnaissance. Each of these approaches provided useful data that the others did not, and the combination provided a higher degree of certainty than any single approach.

The primary comparative results were that at the Kirtland site, helicopter magnetometry showed two areas of concentrated magnetic anomalies within one of the target areas that was not detected by LiDAR or orthophotos. However, at both the Kirtland and Victorville sites, LiDAR showed areas of extensive cratering that had only a low density of anomalies in the helicopter magnetometry. Ground-based transects cross-validated the helicopter magnetometry results and established background levels of magnetic anomalies that were beyond the resolution of the helicopter magnetometry (see Figure 16).



Helicopter and transect results for Kirtland Target N-3. Source: ESTCP. Two areas of concentrated magnetic anomalies, N3-AOI*-7 and N3-AOI-8, were not visible in the LiDAR and orthophotos data since these areas showed no surface disturbance.



Helicopter and transect results for Kirtland Target NDIA. Source: ESTCP. This area shows a low density of magnetic anomalies compared to background, although the target cross-hairs are visible in the orthophotos and craters can be seen in the LiDAR data.

*AOI = area of interest

Figure 16. Example Helicopter and Ground-Based Transect Results.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Table 1 presents actual costs for the Kirtland, Victorville, and Former Camp Beale demonstration sites, and estimated costs for production sites of several additional sizes. The figures for two production sites are planning-level estimates, assessed to be accurate +/- 20% at the time of this report. Per-acre costs for the Kirtland site were higher since four rather than two LiDAR flights were conducted, and one rather than two orthophoto sets were created. The Victorville configuration, with one LiDAR/orthophoto flight and one additional LiDAR-only flight, is considered representative for a production site where it is important to detect both targets and individual small features and was used at the Camp Beale site. Estimates for the larger sites are based on URS' previous experience with LiDAR and orthophoto collection projects and interviews with industry sources. All figures are in 2006 U.S. dollars and costs were updated in June 2007. All projects listed can be completed in less than one year; therefore, no discount factor has been applied to the figures.

Table 1. Actual and Projected Costs.

Project Parameters	1,000-Acre Site	Kirtland	Victorville	10,000-Acre Site	Former Camp Beale	50,000-Acre Site	115,000-Acre Site	250,000-Acre Site
Project area size (acres)	1,000	5,000	5,640	10,000	18,000	50,000	115,000	250,000
Project area size (hectares)	404	2,020	2,279	4,040	7,272	20,200	46,460	101,000
LiDAR flights:								
300 m (LiDAR only)	1	2	1	1	1	1	1	1
450 m (LiDAR and 10-cm pixel imagery)	1	1	1	1	1	1	1	1
900 m (LiDAR and 20-cm pixel imagery)	0	1	0	0	0	0	0	0
Total LiDAR flights	2	4	2	2	2	2	2	2
Total LiDAR point density (pts/m ²)	~10	20	~10	~10	14	~10	~10	~10
Orthophoto pixel size (cm)	10 and 20	10	10	10	10	10	10	10
Costs:								
Fixed Costs	\$							
Mob/demob	15,000	15,600	23,100	21,000	21,800	30,000	45,000	50,000
Planning/preparation	8,000	15,000	9,200	12,000	15,000	15,000	20,000	22,000
Project management	10,000	15,000	10,000	10,000	25,000	40,000	80,000	100,000
Site work	0	0	0	0	0	0	0	0
Equipment cost	0	0	0	0	0	0	0	0
Start-up and testing	0	0	0	0	0	0	0	0
Subtotal fixed costs	33,000	45,600	42,300	43,000	61,800	85,000	145,000	172,000
Variable Costs	\$							
Data acquisition	25,000	39,900	34,100	64,000	85,300	160,000	355,000	750,000
Data processing	18,000	45,800	35,200	60,000	102,900	250,000	575,000	650,000
Data analysis and GIS products	10,000	94,300	30,000	38,000	68,100	150,000	220,000	260,000
Data reporting and documentation	8,000	13,600	8,500	9,000	12,000	15,000	25,000	30,000
Materials and consumables	500	1,500	1,000		1,500	5,000	10,000	15,000
Other Direct Costs	\$	0	0		0	0	0	0
Subtotal variable costs	\$61,500	195,100	108,800	171,000	269,800	580,000	1,185,000	1,705,000
Total project cost	\$94,500	240,700	151,100	214,000	331,600	665,000	1,330,000	1,877,000
Total per/acre cost	\$94.50	48.14	26.79	21.40	18.42	13.30	11.57	7.51
Total per/hectare cost	\$233.91	119.16	66.31	52.97	45.60	32.92	28.63	18.58

5.2 COST ANALYSIS

5.2.1 Cost drivers

The major cost drivers for the Camp Beale site largely confirmed the findings from the Kirtland and Victorville sites. These were:

- **LiDAR data density required.** For the Kirtland site, four LiDAR flights were conducted—two concurrently with digital imagery collection and two LiDAR-

only flights. For the Victorville site, one LiDAR/orthophoto flight and one LiDAR-only flight were conducted. For Camp Beale, two LiDAR flights were conducted.

- **Orthophoto data density required.** For the Kirtland site, two sets of digital images were collected, and orthophotos were created at 10-cm and 20-cm pixel sizes. For the Victorville site, only 10-cm pixel size was collected. For the Victorville and Former Camp Beale sites, only 10-cm pixel orthophotos were acquired.
- **Accuracy and precision requirements.** A higher level of survey control was needed at the Camp Beale site than for production sites, including collecting 16 control points, 10 test craters, and four vertical control structures. For production projects, fewer survey control points and vertical control structures would likely be needed. However, the cost of project control is small relative to that of data acquisition and processing, and the cost savings would be relatively minor.
- **Site location and logistics.** The Camp Beale site location affected project costs both positively and negatively. The site is situated close enough to the Yuba Airport so as not to require establishing a fuel cache on site or to require the aircraft to land. Negative factors included the proximity of the Phased Array Warning System (PAWS) radar installation, which interfered with the LiDAR equipment requiring additional data processing, and the excessive ambient temperatures experienced during the data acquisition flights which limited the flights to the early morning hours and required slower aircraft speeds.

In addition to the cost drivers listed above, costs for production sites will be affected by the following additional factors:

- **Site size.** Larger sites achieve cost savings through amortization of fixed costs such as mobilization and project planning, as well as through increased efficiency in data acquisition and processing. This effect can be seen in Table 1.
- **Vegetation conditions.** Highly vegetated sites may have higher costs due to the requirement for additional LiDAR passes to achieve sufficient density of points reaching the ground surface. Alternatively, it may be possible to achieve sufficient vegetation penetration by specifying the use of higher speed sensor equipment.
- **Permitting and site access constraints.** DoD sites with sensitive, high-security areas may have higher costs. However, such conditions would typically affect only pre-flight planning and equipment mobilization costs rather than data acquisition, processing, and analysis costs. Sites with environmental constraints do not normally impose significantly higher costs for LiDAR and orthophotography since the airborne nature of the technologies does not typically affect sensitive species or environments.

5.2.2 Cost Sensitivities and Additional Potential Savings

Additional savings could be realized through either of the following methods:

- Acquiring orthophotography with a larger pixel size. The cost of acquiring and processing orthophotography rises dramatically for smaller pixel sizes, and acquiring orthophotos at 20-cm pixel size rather than 10-cm would reduce the data acquisition and processing costs by 30–35%. The utility of such photos would be lower since their resolution will not allow discrimination of smaller features. At highly vegetated sites, orthophotos are inherently less useful, and orthophotos with larger pixel sizes may be acceptable or orthophoto collection may be eliminated altogether if pre-existing orthophotography is available and its positional accuracy can be verified. However, at relatively open-sky sites, site managers should consider acquiring 10-cm pixel orthophotos. Experience during both phases of the WAA Pilot Program has shown that these are significantly more useful than orthophotos with larger pixel sizes.
- Acquiring lower-density LiDAR data. Eliminating the assumed second LiDAR flight and thus collecting LiDAR only with the 10-cm orthophoto imagery would reduce costs by 25 to 30%. The ability of the resulting LiDAR data set to discriminate features would be reduced; however, this might be appropriate if the LiDAR data was to be used only to discriminate large features such as bombing targets or roads rather than smaller features such as craters. Alternatively, a faster LiDAR sensor could be used that could meet LiDAR data density requirements from a single pass.

Some additional cost savings could potentially be achieved by establishing Service- or DoD-wide standards for data acquisition, GIS data product creation, data delivery formats, and project reporting.

5.3 COST COMPARISON

Cost comparisons with the other innovative technologies demonstrated as part of the ESTCP WAA Pilot Program will be made in the Final Report for the WAA Pilot Program.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Key factors that affected project costs are summarized in Section 5.2, Cost Analysis, including sensitivity to site-specific conditions and areas for potentially reducing costs in future applications. Learning curve effects were relatively small over the three demonstration sites due to the use of experienced vendors.

6.2 PERFORMANCE OBSERVATIONS

LiDAR and orthophoto data collected for this demonstration met the performance criteria related to data collection, data procession, site coverage, and positional accuracy established for each site. Details are presented in the Final Report for the Kirtland and Victorville site and the Final Report Addendum for the Former Camp Beale site.

6.3 SCALE-UP

No technical impediments were noted that would affect scale-up from demonstration-scale to full-scale implementation. Both LiDAR and orthophototgraphy are in wide commercial use on large sites nationwide.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The Former Camp Beale site presented a much larger number of ambiguous features than the first two sites examined. This site may be representative of some formerly used defense sites that have a complex history of munitions- and non-munitions use. Most of the ambiguous features identified were shallow depressions that resembled craters in the LiDAR and orthophoto data, which could not be distinguished from munitions craters using LiDAR and orthophotos alone. Subsequent field work showed that only a minority of these had a positive magnetic response. However, LiDAR and orthophotos were successfully used to locate these features for subsequent field investigation. Given the large size of the site, the cost savings from identifying and prioritizing these ambiguous features would be substantial compared to using other methods.

6.5 LESSONS LEARNED

Results from all three sites support the general premise of the WAA Pilot Program that LiDAR and orthophotos should be the first technologies to be deployed after completion of the ASR and the initial CSM. At all three sites, LiDAR and orthophotos were successful at revealing and verifying the broad picture of munitions use. LiDAR, especially, was very successful at delineating targets and crater fields, along with ambiguous features that warranted investigation. The two technologies complemented each other well, each providing data that the other did not. Both technologies provided base data that were useful for planning subsequent investigation. Since vendors generally offer the two technologies together, it makes sense to acquire both at future production sites.

At the Kirtland site, two AOIs were identified using magnetometry that were not detected using LiDAR and orthophotos, presumably because these areas did not leave any indications on the

ground surface. However, at the Kirtland and Victorville sites, LiDAR and orthophotos were used to identify bombing targets that had little to no magnetic signature, possibly due to earlier cleanup efforts. In this sense, LiDAR and orthophotos complemented the magnetometer and EMI technologies, and the combination resulted in a higher level of confidence than either separately.

The Former Camp Beale site was a logical extension of the WAA Pilot Program to a more complex site. The site was more challenging in at least two dimensions. First, the area had been used for a wider variety of munitions-related activities than the previous sites, including not only bombing ranges but also firing and training ranges. Second, the site was used for a much wider variety of non-munitions-related activities, especially including mining exploration. As a result of both these factors, the Former Camp Beale site presented a much wider range of potential features. Nevertheless, the overall objectives of the demonstration were met:

- LiDAR and orthophotos were used to identify potential bombing targets and firing ranges with a high level of confidence.
- LiDAR and orthophotos were used to correct what appeared to be an erroneous target location in the initial CSM.
- LiDAR and orthophoto data were used to produce lists and locations of ambiguous features for further investigation.
- LiDAR and orthophoto data provided information on topography and vegetation that was used to plan magnetometry and EMI transects.

The primary difference between the Former Camp Beale site and first phase sites was that at Former Camp Beale there were a larger number of features whose origins could not be determined using the LiDAR and orthophoto data alone. The history of mining exploration at the site was particularly problematic since this activity produced depressions that could not easily be distinguished from potential craters. However, the origin of most or all of these features could be resolved with field investigation using handheld magnetometry.

These results emphasize the appropriate use of LiDAR and orthophotos at the beginning of the site investigation process, and the importance of following the use of LiDAR and orthophotos with technologies such as magnetometry and EMI that directly detect munitions components.

6.6 END-USER ISSUES

End users were not directly involved in the demonstration of LiDAR and orthophotos. However, end users are represented on ESTCP's WAA Advisory Group for the WAA Pilot Program. Further information on end-user issues is presented in the Final Report for the WAA Pilot Program as a whole.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The only specific approval needed to carry out the demonstration was flight clearance over parts of Beale Air Force Base, which is adjacent to the Former Camp Beale demonstration site.

Obtaining this flight clearance required approximately one month. Generally, no special licenses or permits are needed to carry out surveys using LiDAR and orthophotos.

Further interactions with government and quasi-government validation programs are discussed in the Final Report for the WAA Pilot Program as a whole.

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
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